NBDL- M003

TASK DEPENDENT DIFFERENCES AND INDIVIDUAL DIFFERENCES IN DUAL TASK PERFORMANCE

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October 1980

NAVAL BIODYNAMICS LABORATORY
New Orleans, Louisiana

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NBDL-M003	2. GOVT ACCESSION NO.: AD-A099986
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): Task dependent differences and individual differences in dual task performance.	5. TYPE OF REPORT & PERIOD COVERED: ~~Monograph~~ Rept. for 1 March 1978-30 June 1979
	6. PERFORMING ORG. REPORT NUMBER: EPL-79-4
7. AUTHOR(s): Christopher D. Wickens, Sheilagh J. Mountford, William Schreiner	8. CONTRACT OR GRANT NUMBER(s): USN N00302-78-M-3378
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Department of Psychology, University of Illinois, Champaign, Illinois 61820	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Project No. F58524; Task Area ZF5852400; Work Unit MF58 524-002-5027
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Medical Research & Development Command, Bethesda, MD 20014	12. REPORT DATE: 18 October 1979
	13. NUMBER OF PAGES: 49
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Naval Biodynamics Laboratory, Box 29407, New Orleans, LA 70189	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited

MF58524002

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

ZF58524006

18. SUPPLEMENTARY NOTES

BEST AVAILABLE COPY

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

time-sharing, attention, abilities, factor analysis, dual task performance, hemispheric laterality

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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October 1980

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Preface

In order to measure comprehensively the effects of adverse environments on human performance, Kennedy and Bittner (1977) have argued the necessity of identifying tasks that have stable performance measures. In this endeavor, they have initiated the development of PETER (Performance Evaluation Tests for Environmental Research). PETER is a battery of neuropsychological information processing and cognitive tasks that both reflect individual differences in CNS functioning and are stable over long term repeated administration.

It has been recognized that a considerable portion of the processing demands imposed upon the controller of Navy weapons systems involves the concurrent performance of tasks (time-sharing). This recognition has dictated that the search for components of PETER must in addition to single task abilities include those that assess time-sharing or dual task performance. Therefore, the present investigation was conducted with the objective of establishing the existence of individual differences in time-sharing ability and to further identify their qualitative nature.

INTRODUCTION

Time-sharing may be loosely defined as the concurrent performance of two separate tasks. The concept of individual differences in time-sharing ability may be considered in two different senses. In the first sense, this simply refers to differences between individuals in the efficiency with which a given pair of tasks can be performed concurrently. In this manner we might contrast the novice pilot, who cannot easily control the pitch and yaw of the aircraft, while carrying on a conversation with the flight instructor, with the skilled pilot who can easily excercise flight control, and converse in parallel. A difference between these two in their time-sharing ability is clearly evident--yet the source of this difference can be directly attributed to differences in the degree of automation of the flight control task. For the skilled pilot this task simply requires less attention and therefore can be more effectively shared with the attention-demanding conversation.

A more restrictive conception of time-sharing ability, one that cannot be attributed to the automation level of the component task, examines individual differences in the mechanisms by which two tasks are time-shared: either in the total amount of capacity mobilized in concurrent performance, or in the fine-structure of task interweaving, the perceptual sampling or response strategies employed (Damos and Wickens, 1980, (in press); Wickens and Benel, 1979; Fisher, 1975; Hawkins, Church and DeLemos, 1979).

The distinction between time-sharing in the first sense and the second sense is crucial. Individual differences in sense 2 will of course be manifest as individual differences in sense 1, but the converse is not true. In the present treatment we shall refer to time-sharing abilities only in the second, more restricted sense of the concept.

The conventional approach adopted in seeking evidence for individual differences in time-sharing ability (in either sense 1 or sense 2), is through correlational studies. A number of subjects perform tasks singly and concurrently. The pattern of correlations between single and dual task scores or between both of these and a complex criterion variable is then examined to determine if (a) there is a substantial portion of variance in dual task performance that does not correlate with performance under single task conditions or (b) dual task measures provide additional predictive validity to the criterion variable. If either of these results are observed, then it is concluded

that individual differences in time-sharing exist. Yet this inference is only valid for time-sharing in the first sense. It is possible that those individuals who are better dual task performers, achieve this status simply because the component tasks are more automated. If furthermore the differences in automation are not reflected in single task performance levels (e.g., Bahrick and Shelley, 1957; Garvey and Taylor, 1959), then the observed pattern of low correlation between single and dual task performance will emerge.

In fact, on logical grounds it seems difficult to ever discount the role of differences in automation in producing differences in time-sharing, when employing a pure correlational approach with only two tasks investigated. Under these conditions, therefore, affirmative evidence for individual differences in time-sharing ability in sense 2, is extremely hard to obtain.

Two alternative solutions are however available. One can examine the fine grained nature of dual task performance--the structuring and timing of responses, or the sampling and switching of attention between tasks--to determine if individual differences in these patterns correlate with differences in dual task performance efficiency. It is assumed here that the microanalysis reveals patterns that are by definition unique to the time-sharing environment, and therefore must reflect a time-sharing ability. Alternatively one can seek evidence for the existence of a general, transituational time-sharing ability that transcends qualitatively different dual task combinations. This might be described as an "A-factor" in attention, analogous to the classic G factor of intelligence. If an individual who performs well in one dual task pair, also performs well in a different dual task combination, despite the fact that the two tasks in the first pair have little in common with the two in the second (e.g., their single task correlations are low), then it may be concluded that something about the mechanism of the task-sharing transcends the two pairs, and reflects a high level of the time-sharing ability in sense 2, for the individual in question.

It should be emphasized that the <u>absence</u> of such an "A factor," does <u>not</u> mean that time-sharing abilities that are restricted to a particular dual task combination (e.g. dual axis tracking) do not exist. Only, as pointed out above, it then becomes difficult to identify these on the basis of correlational evidence (between single and dual task performance) alone. Micro analysis <u>must</u> be undertaken. In this regard, it is important to realize that time-sharing ability may not be a single general trait, but may be comprised of several more or less independent sub-abilities, some combination of which are partic-

ularly functional for a specific dual task combination for a given subject. Hawkins, Church and deLemos (1979) describe three types of subskill which they consider may be important in the performance of concurrent tasks. Firstly, an ability to process multi-information sources in parallel somewhere within the information-processing system. Secondly, an ability to re-allocate processing resources when processing must proceed in series, or alternatively an efficient switching strategy of attention away from one source and into another quickly reducing the dead time switch (Laberge, 1973). Finally, an ability to automate one or more sources of information-processing, which will depend on the difficulty and nature of the task being performed. This last subskill is similar in nature to that defined by Pew (1975) in observing a shift in control type with practice from lower closed-loop control to a more open-loop control mode in the development of tracking skill. As described above the latter category is not classified as a time-sharing skill in the more restricted second sense of the term.

In what follows, correlational studies of dual task performance will be reviewed, including these whose evidence is ambiguous with regard to sense 2 definition, as well as those that allow strong inference concerning the existence of this ability. Following this, some evidence for the particular characteristics of the observed time-sharing skills will be reviewed.

In the following sections, three categories of research will be reviewed. As described above, correlational studies may be partitioned into two groups. Those that deal with only a specific pair of time-shared tasks, examining dual task correlation either with single task performance or with a complex criterion test (e.g., success in flight training), and those that enable identification of the transituational "A" factor. The third category concerns the relation between part and whole task performance of a complex task. According to this technique the measures of part-task performance are used to estimate and predict performance on the whole-task. When past task performance underestimates the performance levels attained in whole-task performance, this is assumed to be due to a time-sharing ability overriding the predicted decrements.

Correlational Time-sharing Studies with One Task Pair

In one of the earlier investigations of this type, Melton (1947) contrasted performance on a rotary pursuit task, tested singly and when performed together with a light cancelling task, thereby requiring divided-attention. Only a .03 increment in the predictive validity of a test battery for pilot selection was achieved by including this additional divided-attention requirement. The reason for the lack of increase in predicting success could have been due to the fact that candidates were not given enough practice on the dual-task conditions to obtain reliable measures of their time-sharing skills.

A more thorough use of a divided-attention test was made by Trankell (1959) using fourteen assessment variables to select pilots for Scandinavian Airlines Systems. One of the tests, the simultaneous capacity test, required subjects to trace patterns of circles and connect them with straight lines to a metronome beat using both hands, while simultaneously solving various intellectual problems. During a five year time span 780 subjects were tested, 363 of whom were on co-pilot courses, and the validity of the selection system was checked against the number of dismissed pilots and the remaining pilots flying skills. Subjective ratings were the only scores taken to evaluate eventual flying abilities. Bi-serial correlations showed $R_{bis} = .55$ for the measure of simultaneous capacity with subsequent skill level in flying. The other high correlation was that taken for a test of motor skill performance, $R_{bis} = .43$. The impressively large sample size tested makes this study particularly encouraging for the inclusion of a dual task performance measure in enhancing the techniques used for pilot selection, because after all it does provide an analogue to the real-world task of performance in the cockpit.

More recent tests on the predictive validity of time-sharing tasks to determine flight success have been performed at the University of Illinois. Damos (1978) was concerned with the amount of attention that was left over during the performance of the flight task. This 'residual' attention is of particular concern when the pilot is required to attend to other tasks often of an infrequent nature but of a high priority. Residual attention is seen as having special importance when higher-order levels of performance are required and therefore may be an important criteria to determine the selection of superior pilots.

Damos (1978) asked subjects to track with one hand and perform a choice Reaction Time (RT) task with the opposite hand using between 1-3 bits of stimulus uncertainty. Adaptive-logic was used to keep the performance on the tracking

task within specified error limits. The additional performance variance was thus reflected in the choice RT, which served as an index of the subjects' residual attention. One group of subjects performed the tasks before and after flight training, and the other only after flight training. Multiple correlations of flight checks with RT values for 1-3 bits of stimulus uncertainty were calculated, revealing $\underline{R}$ = .68 with a 30 hour flight check. Performance levels indicated an increase in the amount of residual attention available with practice in flying and showed a higher eventual level when the test was administered both before and after flying. The use of a residual attention test is certainly a short-range predictor of success in dual-task situations, since the multiple-correlations increased as a function of flight-training, and it was suggested that this kind of test may have some useful long-range predictive powers too.

The range and consistency of individual differences in attentional capabilities and their validity as predictors of flight success were addressed by North and Gopher (1976). In their procedure, each subject's maximal performance on a particular single task was measured and this was assumed to reflect his individual capacity. Then they varied the subsequent task priorities in divided-attention situations. Comparison of single with dual performance was inferred to indicate the individual's ability to voluntarily control the allocation of attentional capacity. A one-dimension compensatory tracking task was time-shared with a digit processing RT task. Dual task conditions involved both equal task priorities; and priorities favoring one task over the other. Discriminative validity of this time-sharing task was tested initially on eleven instructors and thirty-two student pilots.

North and Gophers' results showed that the flight instructors retained a greater proportion of their total capacity in dual task conditions than did the student population, suggesting that the flight instructors were better time-sharers. An interesting difference between the two groups indicated that subjects during practice put more of their capacity on the 'easier' task in dual conditions. For the flight instructors the easiest task appeared to be the tracking task, and for the students the digit-processing task. This result leads to the conclusion that the direction of attention allocation to enhance performance is determined by the experience of the subjects.

The tracking-RT combination was further used to reflect the predictive validity of several dual-task performance measures to the passing criterion for obtaining a private pilots license. Students on a flight course were divided into high and low potential groups by their instructors and their performance

on single and dual task measures were correlated. The measures that most clearly separated the ability of the two groups related to dual task, not to single task performance.

North and Gopher also computed attention manageability scores reflecting the ability of a subject to change the allocation of attention to meet the required demands of changing task priorities. These reliably discriminated the dichotomy of high vs. low potential students. Furthermore, as the task priorities varied across trials, all subjects were very consistent in their division of attention between the tasks, usually favoring one task more than another even in equal demand conditions, but remaining within this bias throughout the experimental shifts. Subjects were seen to make almost linear adjustments to the changes in demand between the actual and desired levels of performance, which was unrelated to either single or dual performance levels. With practice more spare capacity became available and subjects allocated this capacity to the 'easier' task. It appeared that flight instructors were better time-sharers partly because tracking was less difficult and thus less demanding than the digit task, for the students tracking drained more resources away and led to worse overall performance.

In a fifth, predictive investigation, Jacobs (1976), using dual task measures similar to those employed by North and Gopher found these to be no more predictive of success in flight training than were single task measures. A critical fact that may produce these seemingly discrepant results could be the amount of practice that subjects receive in dual task conditions before a stable and thus more reliable index is obtained, this of course may take longer to reach than in single task performance.

As argued above, the studies described in this section, being restricted to time-sharing between a single pair of tasks cannot really discount the possibility that level of automation, rather than time-sharing ability per se, is the critical discriminating variable that generates the instances of favorable predictive correlations. Only Gopher and North's examination of the manageability score provided some specific evidence of the time sharing ability in sense 2.

The Transituational Time-sharing Ability: Correlations between Multiple Pairs

A pioneering investigation by McQueen (1917) was not concerned with the use of a time-sharing index to determine flight success, but with the actual nature of the attentional mechanism within a dual task paradigm. McQueen hypothesized that if a general factor of time-sharing did exist, performance on dual

task combinations with no common elements should correlate highly with performance on other dual task combinations. He used eight different tasks in four pair-wise arrangements, simple tasks such as counting aloud by threes were paired with other simple tasks such as crossing out Os on a page. The subjects tested were 35 twelve-year olds, who performed tasks singly first then two dual task pairs and then each singly again. McQueen's results showed that with more practice subjects retained more of their single task performance levels in the dual conditions. Furthermore, the rank order of their performance levels for single task performance was entirely different from that obtained in dual conditions, so subjects who were good performers of the tasks alone were not necessarily good time-sharers. While this correlational pattern suggests the existence of combination-specific time-sharing abilities, the evidence for a general ability was absent. No significant partial correlations were observed between dual task combinations sharing no common elements. Also there was no correlation between a subject's change in rank position between single and dual task conditions across the various combinations. Both of these factors argue strongly against a general factor of time-sharing ability. However, it should be remembered that McQueen's study uses subjects of twelve years, which may contribute to the lack of support for a general factor. As Wickens and Benel (1979) note, differences in the time-sharing of children may be attributable to changes in automation, functional separation, deployment of resources and expanded capacity. It is quite possible therefore that the results of McQueen's study are confounded to some extent by age dependent effects.

A more recent study was conducted by Sverko (1977) on adults in an effort to find evidence for a general factor of time-sharing skill. This study was conducted in order to test the supposition that the ability structure underlying concurrent task performance differs in nature from the ability structure underlying solitary performance of the same task. Sverko (1977) tested 60 subjects on four tasks singly and in all pair-wise combinations using a rotary pursuit task, mental arithmetic, two-choice auditory discriminations and choice RT to visual digits.

All dual task performance levels showed a significant time-sharing decrement compared with performance on the same single task. The correlations calculated between each task performed singly and with the same task in dual task situations were all positive, ranging between .5 and .9. It thus appears that individuals' performance on the single tasks was closely related to their ability to perform in time-sharing conditions. A Principle Components Analysis was then performed to

extract five factors, four being task specific and one general "A factor" of time-sharing ability. The analysis showed that 79% of the total performance variance was accounted for by the four task specific factors, and the general fifth factor only accounted for 4%, an insignificant source of residual variance. Correlations between performance of the three non-overlapping task pairs was between -.07 and .06, arguing against a common factor contributing to concurrent task performance. These two findings provide no evidence for the existence of a general factor determining time-sharing performance.

The kind of factorial analysis used by Sverko has also been implemented by Fleishman and his co-workers (e.g., 1960, 1965) in various test batteries to show high inter-correlations between dual task performances. It should be kept in mind however, that all these tasks included a common element of a time-shared tracking task, which could have determined dual task performance in a time-shared situation. Nevertheless, Adams (1953) did show that the predictive validity of simple and complex tasks to more advanced stages of practice on a complex psychomotor task were higher when using a more complex dual task measure. His results indicate an increase in correlation between time-shared tasks with practice suggesting the existence of a common skill unique to these tasks that developed over time. This skill may relate to a time-sharing ability.

The final "A factor" study to be described here was that conducted by Jennings and Chiles (1977). They make an important point that many researchers using factor analysis techniques to isolate the existence of a time-sharing skill use component tasks of the same basic nature, in other words tasks of a homogeneous type, before testing of the ultimate time-sharing skill. Like Sverko, these experimenters were looking for an orthogonal factor with high loadings for some tasks in complex performance and low for the same tasks performed singly.

Jennings and Chiles used the Civil Aeromedical Institute (CAMI) Multiple Task Performance Battery (MTPB) to measure a variety of skills important to aircrew performance. This Battery consists of six different tasks, structured into two subgroups of three defined as follows. Group A: An RT task to the changes in state of a warning light; Mental Arithmetic; and group problem-solving task requiring short term memory. Group B: A two-dimensional compensatory tracking-task; A pattern comparison task; and a meter monitoring task. Thirty-seven subjects were tested for three days each. Day 1 constituted 15 minutes of training for each of the 6 single tasks in the battery. During Day 2 subjects had 15 min trials on each of the tasks sets A or B followed by complex (concurrent) task performance on the respective three tasks in either group A or B. This

sequence was then repeated for the alternate group. Day 3 involved performance on the complex tasks only, testing group A and B for 30 minutes each.

All single task performance measures were better than those for the same task in complex performance, except for the problem-solving task. Practice effects were significant for the two complex performance scores but not for the single, suggesting the development of a time-sharing skill. Results of a factor analysis extracted seven factors, and provided no evidence for a general transituational time-sharing ability. The first five factors all loaded reliably on individual tasks in the simple (single) and complex (dual) task conditions. Only the 6th factor suggested a task-specific time-sharing ability. This loaded only on the warning light and meter monitoring tasks in the complex conditions. These tasks were orthogonal in single performance and related only in complex performance, indicating the involvement of a higher-order processing ability related presumably to visual scanning and sampling strategies employed in multi element displays. It should be noted that caution is necessary when interpreting their factor analysis. Since the authors used 12 measures and only tested 37 subjects This increases the likelihood that some factors will emerge simply as a function of chance relationships (Humphreys, Ilger, McGrath and Montanelli, 1969).

Part-task Whole-task Training

A method frequently selected to demonstrate the existence of time-sharing is to use measures of part-task performance to predict expected whole-task performance (Bilodeau, 1955; 1957; Fleishman, 1965; Freedle, Zavala and Fleishman, 1968). When part-task measures are shown to underestimate whole-task performance this is viewed as evidence in favor of a time-sharing skill which enhances whole task performance levels. The aim of this approach is to 'formulate laws' where the composition of relatively complex psychomotor activities are described in terms of part-skills and the relations between these measures. However, the tasks used in part-task measures are often capable of being integrated into an automated whole and thus the decrements in concurrent task performance do not necessarily ensue from a combination of two distinctively separate tasks. In other words the results obtained can obscure some of the interesting interferences involved in concurrent task performance. Since the relation between performance of the parts and of the whole is difficult to specify a priori, it thereby becomes difficult to determine if performance on the latter is, in fact under- or over-estimated by predictions from performance on the former. Therefore this category of research will not be considered further.

Demonstrated Dimensions of Time-sharing Ability

Some consideration of time-sharing, indicates that there are a number of possible dimensions along which this ability might be manifest. These represent the output of the micro analysis that becomes necessary to perform when only a single task pair is examined, if automation explanations are to be discounted. The experimental evidence described above provides varying degrees of support for four of these dimensions.

Allocation of resources. Time-sharing will be more efficient to the extent that tasks of greater importance or "payoff", receive a greater allocation of resources. As described above, North and Gopher (1976) observed that an important component of the individual differences that they observed in dual task performance related to the "attention manageability score" that described subjects' ability to allocate attention according to experimenter-defined priorities. Correspondingly Jennings and Chiles (1977) noted that their single time-sharing factor--loading on monitoring in dual task situations--could be attributed in part to priority allocation. Since the monitoring tasks, unlike the others were categorized by the investigators as low priority, these two tasks in complex conditions tap an ability or scanning strategy, to allocate between high and low priority tasks, that is not of course evident when these tasks are performed in isolation.

Switching. Jenning's and Chile's time-sharing factor, while related to priority assessment, also integrally involves the efficient use of an attention-switching mechanism to sample the monitoring displays. Their observation echoes Hawkins, Church and deLemos' assertion that attention switching reflects an important abilities component in dual task performance. In a study of the acquisition of time-sharing skills in the concurrent performance of two discrete visual-manual tasks, one involving stimulus categorizations and one short term memory, Damos and Wickens (1980) noted a change with dual task practice in the inferred latency with which subjects switched attention between tasks. In a second phase of their investigation, they observed apparent changes also in the switching strategy between two time-shared tracking tasks, that emerged with practice. While reflecting differences with skill acquisition, rather than across individuals, these differences may nevertheless be expected to emerge as ability differences are examined as well.

Parallel Processing. Variability in total capacity, or total resources may also represent a dimension of individual differences. Greater capacity would allow a strategy of parallel information processing to emerge in place of a more

serial processing strategy. Damos and Wickens (1980) reported evidence for parallel processing to emerge in both task combinations as a function of dual task practice, along with the switching ability described above. More directly related to ability differences, Elithorn and Barnett (1967) provided evidence for individual differences in channel capacity, related to the ability to process information in parallel between the two cerebral hemispheres.

Performance Strategies. While it is difficult to separate this category distinctly from the three categories defined above, the concept of strategy in time-sharing refers to the efficiency of mapping a particular demand upon a particular capacity, so as to alter the total capacity demands (Welford, 1978). In single task performance an analogy exists to the selection of an optimal "set" for speed vs. accuracy in responding that will maximize information transmission rate, given the nature of the task demands and the physiological "hardware" limitations of the human information processor.

In dual task performances an example of such strategies might relate to how the operator chooses to allocate resources between tasks that are highly automated, and those that are not. Presumably an effective allocation strategy would favor tasks of the latter category, since these will benefit more from the receipt of processing resources. Another example relates to how the subject choses to interleave responses between two discrete tasks (Fisher, 1975). In their skill acquisition investigation, Damos and Wickens (1980) identified three such strategies adopted by subsets of their subjects when performing the combination of the two discrete tasks. A simultaneous response strategy is that showing consistent responding to both stimuli at once. An alternating strategy is one where subjects alternate between one response to one stimulus and then to the other. Chunking is defined as emitting more than 2 responses to one task before switching to the other task. It was assumed, theoretically, that simultaneous response strategies would be optimal because the average interval between correct responses would be the same as that for the average slower single task trials. Alternating would be suboptimal and chunking even slower, because of the time spent away from a task. Damos and Wickens found that strategies did not change with practice but that a simultaneous response strategy generally produced superior dual task performance. It is of further interest to note that the subjects who showed this strategy were those individuals with high single-task dexterity, high timesharing skill level, and those who showed a rapid development of timesharing skill. So, a more efficient performer seems to adopt the most beneficial strategy most rapidly and this in turn enhances time-sharing performance.

In conclusion, there seems to be little evidence in favor of a general 'A' factor of time-sharing ability (Sverko, 1977; McQueen, 1917; Jennings and Chiles, 1977). However, there exist many studies (North and Gopher, 1977; Damos and Wickens, 1980; Jennings and Chiles, 1977; Adams and Hufford, 1962) that indicate some sort of time-sharing skill is in existence with particular task pairs. The consistency of the time-sharing ability is an issue still under debate. The types of tasks used, the extent of practice that subjects receive and their skill level are all crucial issues which make many of the experiments quoted difficult to interpret collectively. Time-sharing studies should be analytical with regard to the stages of information-processing to be loaded, the skill types required and the techniques chosen to isolate this transituational ability.

EXPERIMENTAL RATIONALE

The present experimental investigation adopted a similar approach to that taken by Sverko, (1977) in an effort to identify the existence of either a general, or specific time-sharing ability. An important characteristic of the present study was that the task selection was based upon a careful consideration of human information processing structures. This consideration reflected the emerging realization that processing resources that are brought to play in time-sharing are multi-dimensional. Advocates of this position view attention as being positioned into separate "structure-specific reservoirs", not residing within a single pool of generalized capacity (Navon and Gopher, 1979; Sanders, 1979; Roediger, Knight and Kantowitz, 1977; Wickens, 1979a,b). These structures can be defined by stages of processing involved (Isreal, Wickens and Donchin, 1979; Wickens and Kessel, 1979), cerebral hemispheres of processing (Kinsbourne and Hicks, 1978), and modalities of processing and response (Triesman and Davies, 1973; Harris, Owens and North, 1978; Wickens, 1979b).

As a consequence of the multidimensionality of resources, there are a number of ways in which deployment of these resources in dual task performance could reflect individual differences. Greater "capacity" within a particular resource reservoir for example would be reflected by individual differences in time-sharing efficiency, only of task pairs sharing that same reservoir. The time-sharing factor restricted to visual monitoring tasks, identified by Jennings and Chiles (1977), is an example of this difference. On the other hand, individual differences in the efficiency of a general executive time-sharing mechanism (Moray, 1976) would be reflected in the "A" factor transcending qualitatively different task combinations (McQueen, 1917).

A major interest is therefore placed in the extent to which individual differences in time-sharing, if they exist at all, will identify themselves with qualitatively different task pairs, with task pairs sharing common processing structures or resource pools, or with identical time-shared tasks (e.g., a task shared with itself on the opposite hand). In order to validate the structural resource composition of the tasks selected for investigation careful consideration will be made of the global (as opposed to individual) differences in time-sharing efficiency of different task pairs. Following procedures adopted by North (1977), 4 tasks of relatively separate and different a priori structural composition are chosen to be time-shared in all pairwise combinations. It is hypothesized that the more extensive the overlap in processing structures employed by the two tasks, the greater will be the loss of time-sharing efficiency.

The four tasks chosen may be placed within the proposed representation of the dimension of human processing resources depicted in figure 1. Manual tracking (T) places its heaviest demands upon precise analog response execution; a digit classification task (C) demands verbal-categorical central processing and response selection; a line orientation judgement task (L) demands spatial processing and response selection; and the auditory running memory task (A) demands verbal categorical processing in the auditory modality, with short term memory demands and response selection. These four tasks clearly do not entirely exhaust the partitioning of processing structures in figure 1. To do so in a factorial individual differences study would require a vast undertaking. Yet the 4 tasks clearly allow contrasts to be made that "tap" major dimensions along which processing resources are defined. These contrasts are described in Table 1.

<u>Table 1</u>

Contrasts of Processing Requirements between Task Groupings

1. Input Modality:	visual T C L	auditory A
2. Central Processing:	spatial T L	verbal C A
3. Response	execution analog T	selection discrete C L A
4. Pacing:	forced T A	self C L

In addition to the important criterion of task structure, three other criteria were employed to dictate selection of the specific tasks. These were based upon the guidelines suggested by Damos (1977) for tasks to ensure the development of time-sharing skills.

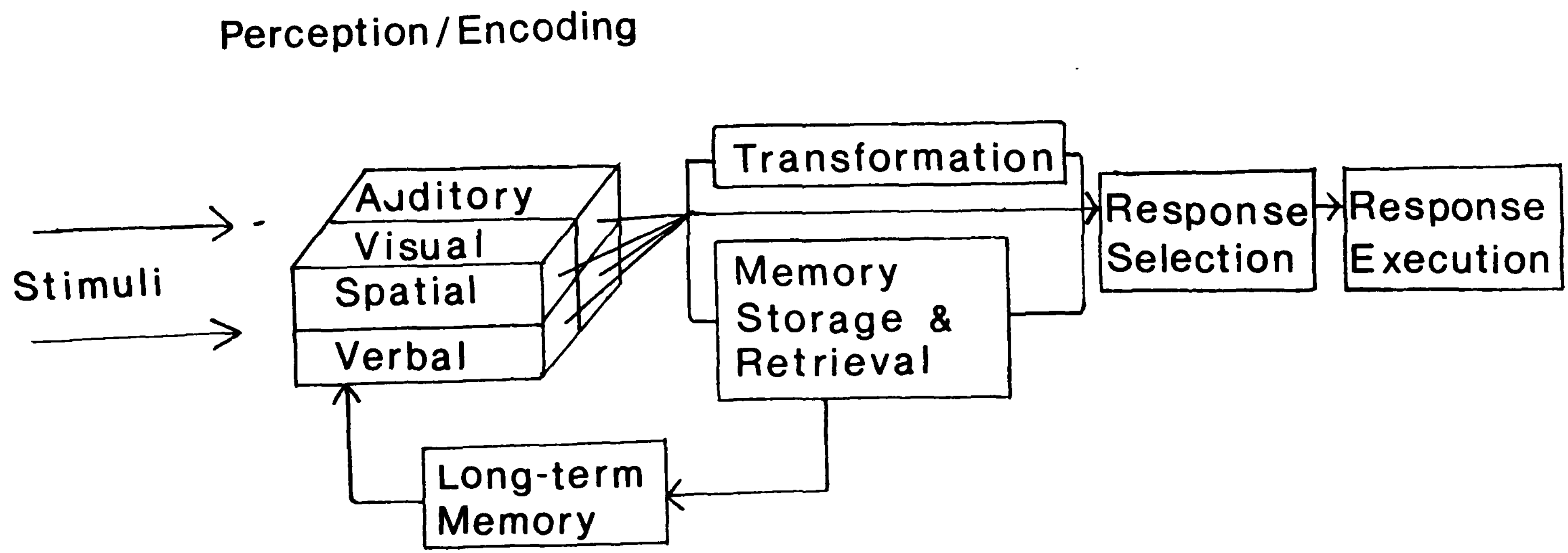

Figure 1: The structural composition of resource pools.

1. The tasks must be of an intermediate level of difficulty, so that neither ceiling performance under single task, nor floor performance under dual task conditions is reached. This will ensure ample variance in performance across individuals in both conditions.

2. Task combinations should be avoided that allow the two tasks to be integrated into a single task. Precautionary measures are taken by employing separable stimulus input sources and requiring different hands for response. Also to be avoided are tasks that allow subjects to alternate between channels of responses on each task, thereby failing to require "true" time-sharing. This is accomplished by incorporating performance measures that impose penalties for neglected tasks.

3. Given the relatively large number of task combinations, performance levels on all tasks must approach a stable assymptote within a reasonably small number of practice trials. This will allow any time-sharing abilities to be revealed more quickly and efficiently.

METHOD

Task Description

Critical tracking task (Jex, McDonnel and Phatac, 1966). This is a one-dimensional compensatory tracking task previously used in dual task experiments by Jex (1967), Jagacinski, Miller and Gilson (1979) and Wickens and Kessel, (1979a, b). The task requires the subjects to apply force to a spring-loaded hand control in a left to right direction to keep an unstable error cursor centered on a vertical bar in the middle of the display. The control dynamics of this task were of the form $Y = \frac{K\lambda}{S-\lambda}$. This provides an unstable positive feedback loop that drives the error cursor to the edge of the display at a velocity proportional to the error and to the parameter λ. The difficulty of the critical task is controlled by the level of λ which was kept at a constant subcritical value of $\lambda = 1.15$. RMS error was recorded as the performance measure. The critical task, being force-paced in its demands, was chosen to place heavy demands on response and spatial encoding stages within the information-processing system.

Number classification task. This task represents a modification of that previously employed by North (1977) and Damos and Wickens (1980). On the display adjacent pairs of numbers are viewed that vary in size (large/small) and in number value (6 or 3 etc.). This task requires subjects to identify pairs of numbers that possess the same size but are also of different value. If pairs of numbers meet these 2 requirements subjects depress the upper key on a control panel, if not they depress the lower key. For example, the pair 22 demands a lower key press, 45 an upper key press. Subjects were instructed to respond as quickly and as accurately as possible. Each number pair remained on the screen for 3 seconds and if no response was executed within this time period one pair was erased and another pair presented. However, as soon as a response was made the pair immediately erased and another pair appeared. The task was therefore of a discrete self-paced nature within a 3-sec time interval. For every discrete response, RT was recorded and scored either correct or incorrect. This number classification task was assumed to require verbal categorical encoding and transformational stages, using the left cerebral hemisphere.

Visual spatial line judgment task. Subjects were presented with a stationary horizontal reference line across the center of the screen. Two obliquely oriented straight lines were presented in a spatially non-overlapping manner, both either above or below the horizon. The stimulus lines varied both in length and angle of projection. The task required subjects to visually project the 2 inner-

most ends of the lines to their imaginary point of intersection and then decide whether intersection point would be above or below the horizon. If the lines would meet above the horizon subjects were instructed to depress the upper key of the control panel, and if below to depress the lower key. Once again subjects were instructed to be as fast and as accurate as possible in their responding.

Presentation logic and response variables were identical to those recorded in the similar number classification task. This line-judgment task was thus of a discrete self-paced nature, requiring visual-spatial processing, decision making and discrete response selection processes within the information-processing system.

Auditory running memory task. Subjects wore stereophonic headphones and heard either in the left or right ear a series of 38 paced computer-generated letters recorded from a Votrax speech synthesizer. A letter was presented once every 3 seconds with a stimulus duration of .5 sec. The task required subjects to judge whether each letter presented was in alphabetical order relative to the preceeding one (excluding the first letter in every trial). If the letter was judged to be in sequential alphabetical order subjects were required to depress the upper button on the control keyboard, if non-alphabetical to depress the lower button. Once subjects had heard the letter they were requested to make their judgment as rapidly and accurately as possible. This task was of a forced-paced nature, since irrespective of the speed of response the pacing of letters was still once every 3 sec. The auditory task was chosen to load most heavily on auditory processing, acoustic short-term memory, verbal categorical processing, and discrete response selection.

Apparatus

The basic experimental equipment included a Hewlett-Packard 7.5 x 10 cm 1300 CRT display used to display all 3 visual tasks. A Raytheon 704 16-bit digital computer with 24 K memory and A/D, D/A interfacing was used to generate inputs to the CRT and to process responses from the keyboards and control sticks. The computer provided digital signals for a symbol generator that converted them to analog inputs for the CRT display. Performance information stored by the digital computer, was provided on a Gould 4800 line printer in the form of a record of individual keyboard responses and RMS errors.

The subject sat in a light and sound attenuated room, on a chair with 2 arm rests with interchangeable control joy sticks and control keyboard panels. The distance of the control panels could be adjusted according to the length of the subject's arm. The keyboard controls had two 1 cm^2 push button keys, the outer key being higher in position and the inner one lower. The joy stick con-

trol used in tracking was a spring-centered dual-axis manual control of which only the lateral motion was used. The subjects' eyes were approximately 110 cm from the CRT display, with the overall display subtending $\pm$ 1.5° of visual angle. Stimuli for the auditory task were pre-recorded and presented to the left or right ear of the subjects' stereophonic headphones (Figure 2a).

Dual task pairings

Each task was programed so that it could be performed with either the left or right hand. Accordingly panels and sticks were interchanged between arm rests. The auditory task was presented monotonically to the left or right ears, while stimulus presentations for the three visual tasks were offset slightly to the left or right of the center of the display when respectively using left or right hand assignments. The keyboard response assignment for the three discrete tasks was also consistent and compatible. Thus the upper and outer key always indicated a response that was alphabetically sequential (auditory task), an intersection above the horizon (line judgement), or a same size-different value (number classification). In this manner any task pair could be time-shared avoiding confusion as to the appropriate responses for each.

A pilot test was conducted which indicated the performance levels for each task and the difficulty levels were manipulated accordingly to permit a reasonable level of performance without reaching a data-limited performance region.

Subjects

40 right-handed male subjects between the ages of 18 and 23 years volunteered to serve in the experiment. All subjects were students at the University of Illinois in Engineering or Liberal Arts studies. The subjects were paid $3.00/hour for their participation in each of three days testing. They could earn bonuses as a result of improvements in their speed and accuracy of responses across days for dual-task trials.

Experimental design

All subjects performed the same combinations of trials across the days but were assigned to one of two groups (A)BA or (B)AB which determined the handedness combinations of dual task trials to be performed on the practice, and the two experimental days respectively (see figure 2b). Within each day trials were completely randomized for every subject for both of single and dual task trials. Figure 2, showing the dual task combinations illustrates the handedness pairings of tasks for an A or a B subject each day. Irrespective of the grouping all subjects performed the diagonal trials every day, that is a task paired with itself.

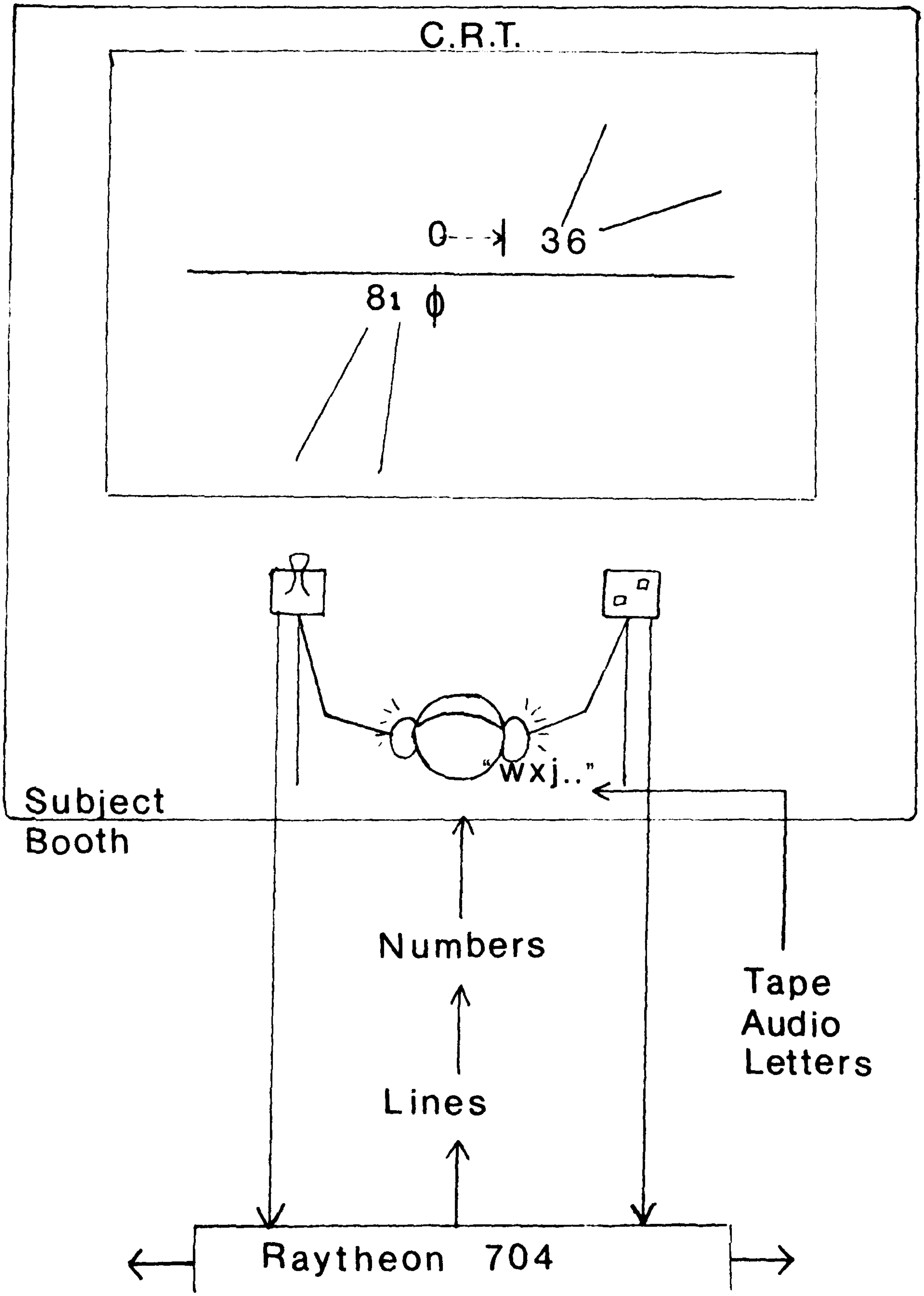

Figure 2a: Schematic representation of experimental set up and display. Note all 3 visual tasks are depicted simultaneously.

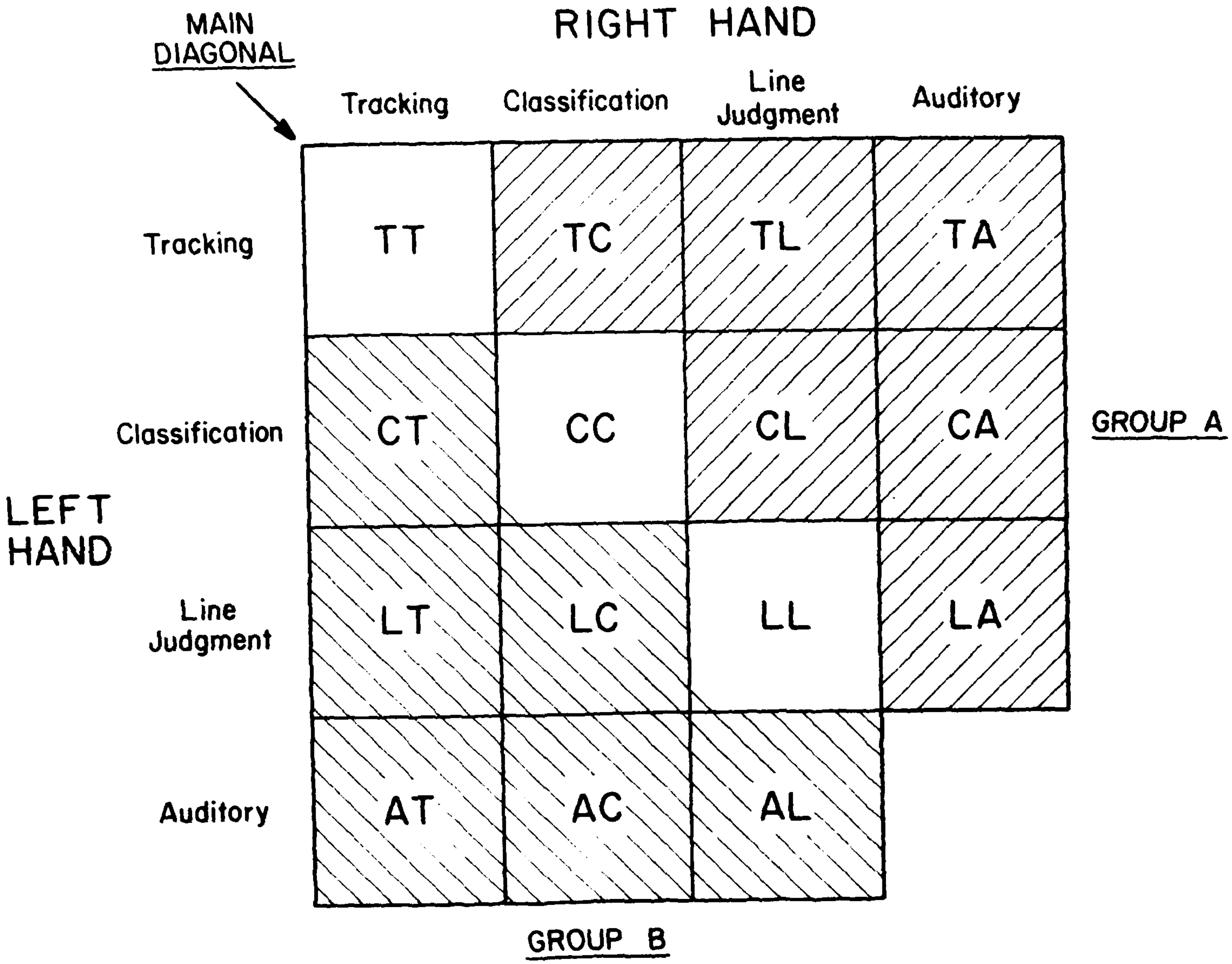

Figure 2b: The 15 dual task conditions and their assignment to the two experimental groups.

It should be noted that the auditory-auditory combination was not included in the current experiment. This decision was made because of the difficulty in synchronizing the dichotic auditory presentation.

Experimental Procedure

All subjects performed for one hour on each of three days of testing. Each trial, single or dual, consisted of a 2 minute period of continuous testing followed by a 2 minute rest period. All the data collected from subjects during day 1 was considered as practice data and was thereafter ignored in the analysis. During the first day of practice the subjects performed each of the four tasks with left and right hand, that is eight single task trials were performed initially. Then depending on the assignment group (A or B) of an individual subject for that day, he then practiced the six heterogeneous dual task trials in the relevant offdiagonal of figure 3, randomly mixed with the three diagonal tasks. On days 2 and 3, all subjects received three practice trials, tracking single, dual tracking and dual number classification. They then proceeded to perform four different single task trials, using the corresponding hand for a task that would be required in the dual task conditions. The last nine trials were dual-task trials either of group A or group B type, randomized in a different individual order. During days 2 and 3 sixteen trials per day were performed, so that on completion of experimental testing every subject had performed every dual task combination with alternative hands.

Procedure

Prior to the presentation of each trial the experimenter informed the subject of the tasks to be performed and changed the panels and sticks accordingly. The trial began within a few seconds of the experimenter leaving the booth. In the case of auditory presentation the subject was instructed over the headphones when the trial was to begin. On discrete tasks subjects were requested to perform as rapidly and accurately as possible. On dual task trials they were requested to divide attention equally between the two tasks, and to avoid any "chunking" behavior in which a series of responses on one task were omitted between responses on another.

A system of performance bonuses was incorporated to encourage high performance and equal allocation of resources between tasks. This system provided a financial incentive of 10¢ when performance on either task of a time-shared pair improved by more than 1 s.d. from its previous day's level. The bonus was increased to 15¢ if both tasks so improved, and was reduced to 5¢ if neither task improved by more than 1 s.d. If either task deteriorated from the previous day

ANALYSIS AND RESULTS

Reliability

Three different variables were recorded on each trial for each of the discrete tasks: The average latency of all responses, the percentage of correct responses, and the absolute number of correct responses. In the auditory task, the latter two measures were equivalent, since the task was force-paced, and the constant number of 38 stimuli was always presented, independent of the subject's response latency.

A major objective of the initial phases of data analysis was to reduce the data from each task to a single variable that would capture both the speed and accuracy dimensions of performance. For the tracking task, the RMS error measure meets this criterion, while for the two self paced discrete tasks (line judgement and classification), the number correct (NC) measure reflects variations in both response latency and accuracy which are the two major dimensions of importance. For the auditory task, a performance index consisting of a linear combination of average latency and percentage errors was computed. This linear combination was also calculated for the line judgement and classification data, using different constants that represented, for each task the variability of RT and accuracy measures.

Day 2 - Day 3 reliability measures were computed on all the various dependent variables (see Table 2), and the performance measures for each task with the highest consistent reliability measures across all task combinations were selected for further analysis. Table 2 indicates these measures to be tracking RMS error (mean $r = .708$), the NC measure for the line judgment (.761) and classification (.809) tasks, and average response latency for the auditory task (.716). While the latter performance measure does not reflect processing accuracy, this measure was nevertheless selected both because of the low reliability of auditory accuracy, and the fact that accuracy was only minimally affected by the experimental manipulations. Unless otherwise stated, these four dependent variables are employed for all further analysis.

Practice

Figure 3 presents the four performance measures as a function of practice under single task conditions, and averaged across the four dual task conditions (three combinations in the case of the auditory task). While all tasks appear to show continued improvement from day 2 to 3, it is important to note that the dual task practice effects essentially parallel those of the single task.

Table 2

Day 2 - Day 3 Reliability Coefficients

MEASURE	SINGLE TASK	PAIRED TASK TR	CL	LJ	AU
Tracking					
RMS Error*	.6929	.8899	.6786	.5050	.7737
Classification					
Percent Correct	.6546	.5064	.7868	.6680	.6780
Number Correct*	.8868	.8186	.8933	.5925	.8592
Average Latency	.8760	.8127	.8524	.3295	.7436
Weighted Latency-Accuracy Measure	.7614	.6139	.8409	.7020	.8003
Speed-Accuracy Tradeoff	.6732	.5769	.7629	.5478	.5196
Line Judgment					
Percent Correct	.5301	.4428	.6424	.7741	.4695
Number Correct*	.7485	.7452	.7790	.7981	.7[illegible]57
Average Latency	.6720	.6321	.2758	.5858	.6830
Weighted Latency-Accuracy Measure	.7127	.6218	.6930	.7156	.607[illegible]
Speed-Accuracy Tradeoff	.4957	.6244	.3665	.7034	.3283
Auditory Task					
Percent Correct	.3322	.1966	.5760	.4158	-----
Average Latency*	.8078	.7099	.7320	.6160	-----
Weighted Latency-Accuracy Measure	.4181	.2463	.6237	.4726	-----
Speed-Accuracy Tradeoff	-.3778	.1072	-.1967	-.0995	-----

*Indicates measure selected.

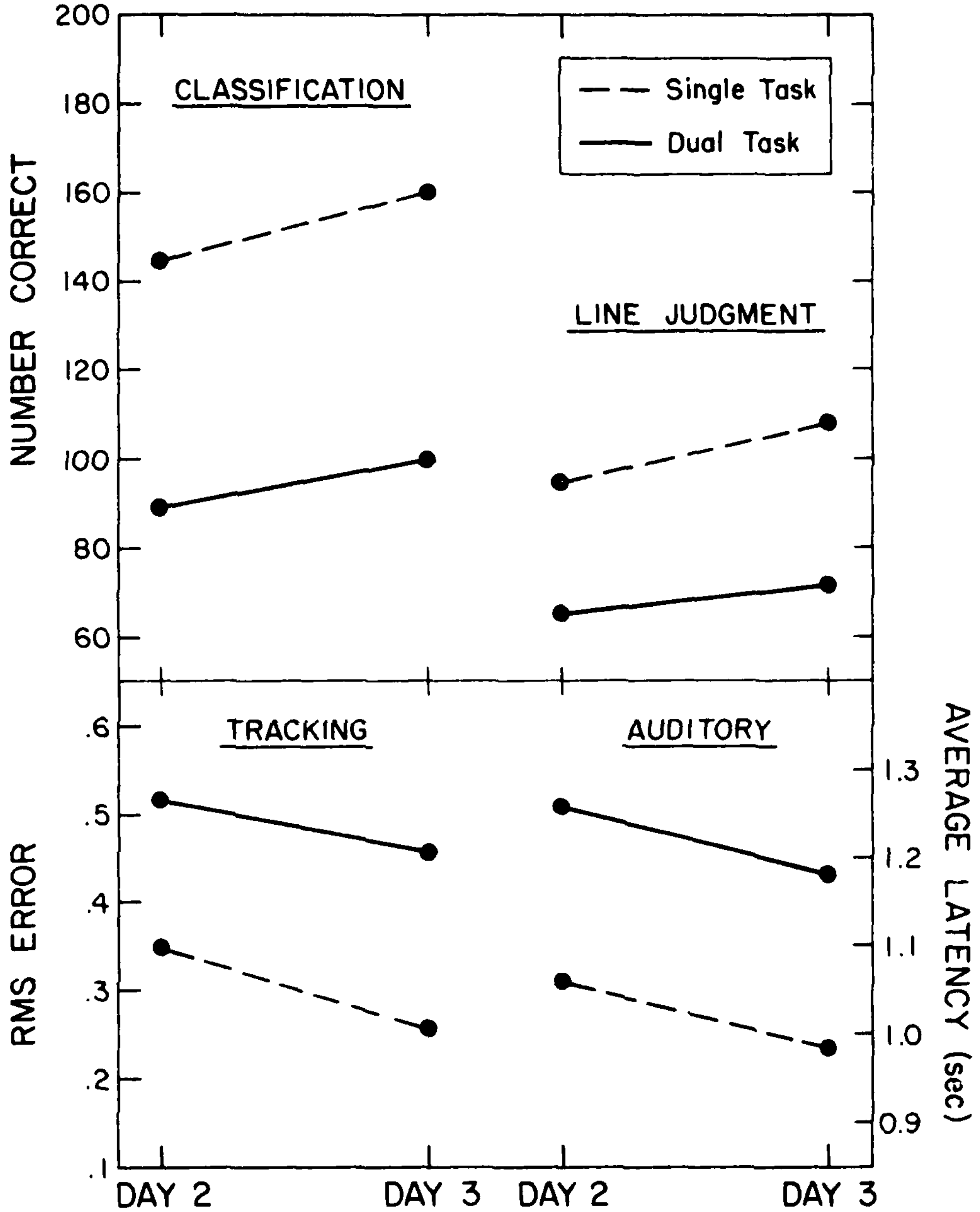

Figure [illegible]: Day 2-Day 3 practice effects in single and dual task performance.

Therefore it may be reasonably concluded that the data collected and resulting inferences drawn are not based upon a period of time-skill development (Damos and Wickens, 1980).

Dual task decrements

Following the previous research of North (1977), a major area of interest in the current investigation concerned the relative time-sharing efficiency of different task combinations. The structural specificity of human processing resources suggests that time-sharing efficiency will be dictated in large part by the overlap of similar processing structures between the tasks involved. As outlined previously, task selection was dictated in part upon consideration of the dimensions of human processing structures, and their underlying processing resources.

The investigation and comparison of time-sharing efficiency across qualitatively different tasks, using different dependent variables presents a challenging methodological issue. This issue is concerned with equating the measurement scales of single-dual task decrements across tasks. The procedure adopted in the current study was similar to that used by Harris and Wickens (Harris and Wickens, 1979; Wickens, 1979a) where an estimate of the performance score variability was obtained for each task, and the single to dual task decrement was then normalized by this estimate. In so doing the following implicit assumption is made: For tasks that are very stable (demonstrate little trial-to-trial variability), a given change in performance from single to dual task conditions represents a proportionately greater loss in efficiency than for tasks that are highly variable. In other words the decrement scores can be viewed as normal deviates.

To estimate this variability, the absolute performance change from day 2 to day 3 within each cell of figure 2 was calculated for each subject. These difference values were then averaged across the various time-sharing conditions and across subjects. The average differences resulting from each of the tasks become the normalization factor by which the single-dual task performance decrements were divided.[1]

Expressed in these terms, the efficiency level of two tasks performed concurrently can be represented as a single point on a performance operating characteristic (POC) space (figure 4). That point represents the decrement on both tasks relative to their respective single task performance levels. Since nor-

[1] Had more than 2 replications of each cell per-subject been collected, then a variance or standard deviation measure would have been employed as this normalization factor.

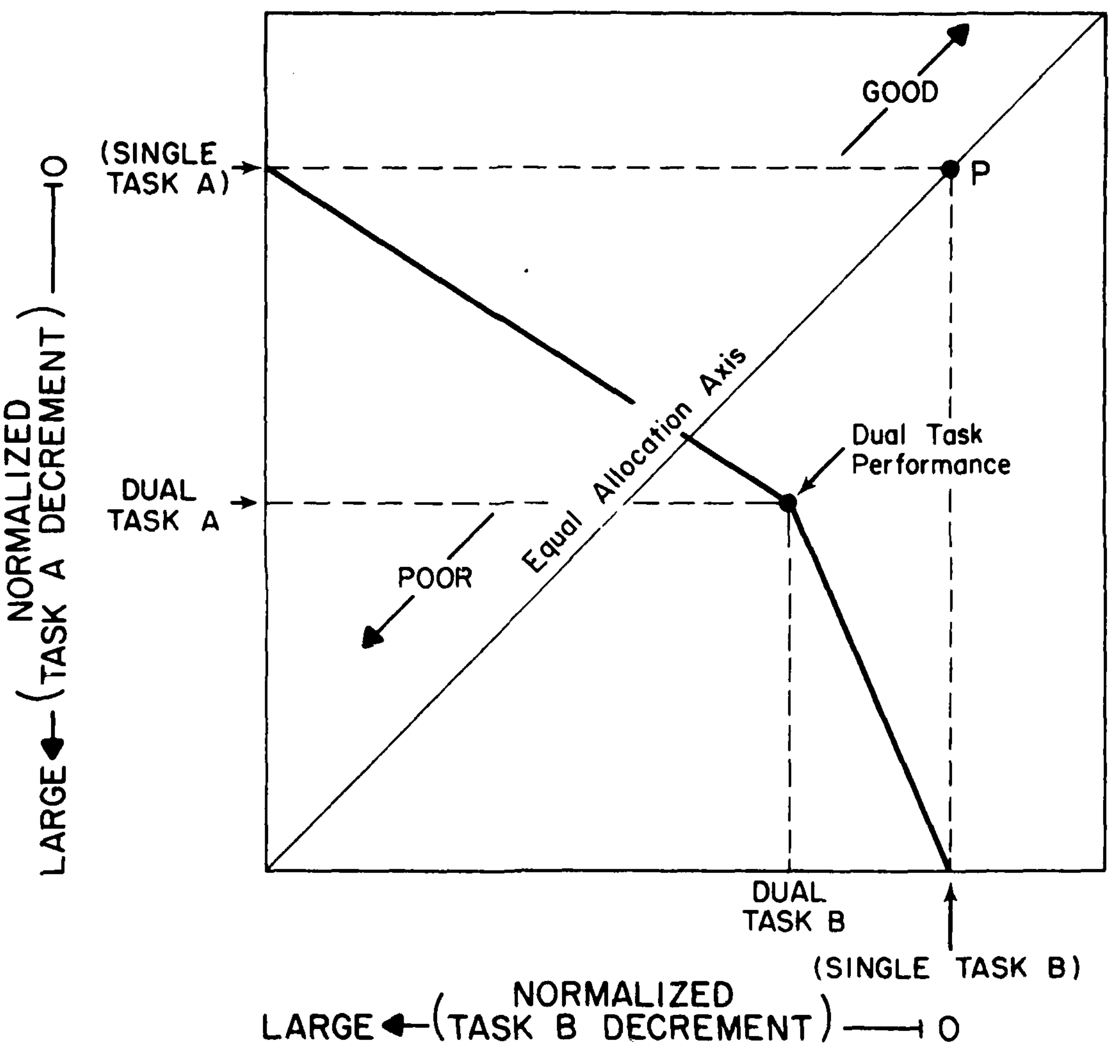

Figure 4: Hypothetical representation of dual task performance within the POC space.

malized difference scores are now employed, the scaling factors and intercepts along both task axes are equivalent. Shifts along the positive diagonal toward the "north east" represent improvements in time-sharing efficiency. Instances of perfect parallel processing (no decrement in either task relative to single tasks) are indicated by the point P in figure 4. Shifts along the negative diagonal represent variations in resource allocation policy. A point toward one axis indicates a favoring of the task along that axis.

Figure 5a-d illustrates these POC representations with the task on the ordinate being tracking (5a), classification (5b), line judgement (5c), and auditory (5d). The abscissa always represents the paired task. (There is therefore some duplication of the points across the different POC's. Only the tasks paired with themselves, are presented once, e.g., TT, CC, LL). Statistical analyses of the data was accomplished using a 2 way (subjects x task pair) multivariate analysis of variance (SPSS MANOVA program). In these analyses, each subject was treated as a bivariate observation whose two dimensions consisted of the decrement on each task from the respective single task performance level. In addition to the omnibus test for the main effect of task pair (the multivariate Wilks' Lambda), planned contrasts were also performed between selected points in each of the figures.

The results of the MANOVAs substantiate the visual impressions of the apparent differences between task combinations in figure 5. In all cases, there are reliable changes in decrements associated with all the different task pairings. Furthermore, in agreement with North's (1977) findings, these decrements appear to be related to the structural overlap of the tasks involved. For example tasks paired with themselves generally show the larger decrement. In the following descriptions of figures 5a - d, task pairs are referred to by a letter pair (e.g., TA for tracking paired with the auditory task). The interference effects can be described in detail as follows.

Figure 5a: Tracking. The statistical reliability of the main effect of task pair was assessed by the Wilks Lambda multi-variate test. A value of .302 was obtained, yielding an approximate F value of 42.29 ($p < .001$). Figure 5(a) indicates an apparently systematic ordering of time-sharing efficiency. The tracking pair (TT) yields poorest performance (identical processing structures shared between tasks); the auditory pairing (TA) yields excellent efficiency (separate input modality separate response type and spatial vs. verbal central processing); the line judgement and classification tasks, which share the common input modality with tracking, but differ in response type, provide intermediate levels in interference.

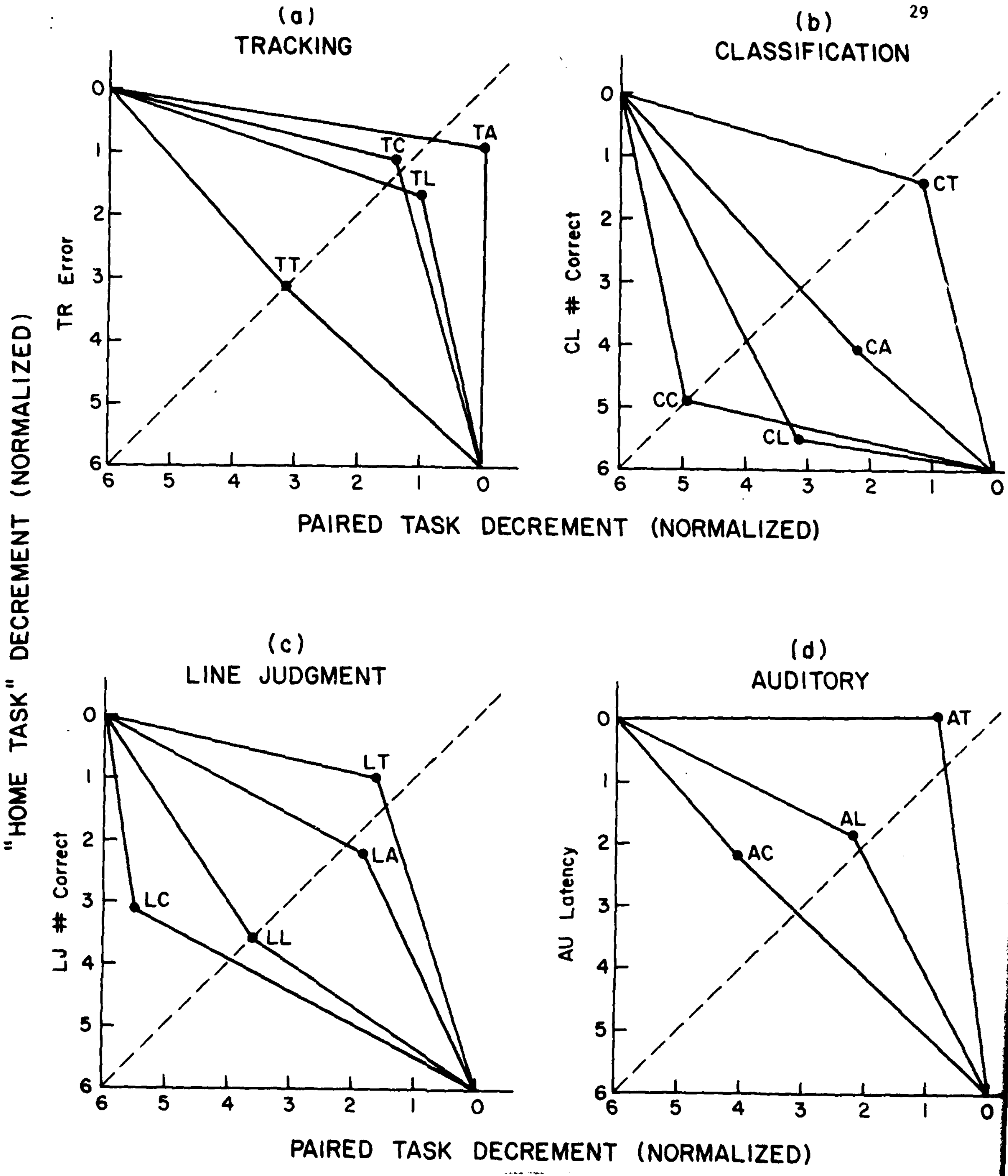

Figure 5: POC representation of dual task performance for the four tasks. (a) Tracking, (b) Classification, (c) Line judgment, (d) Auditory.

The following three contrasts were performed, and these serve to validate the effects described above: TT vs. [(TC + TL)], $T = 9.52$, $p < .01$; TA vs. (TC + TL), $T = 3.30$, $p < .01$; TC vs. TL, $T = 2.20$, $p < .05$. It is difficult to make a strong inference concerning the latter difference in time-sharing efficiency between TL and TC. This appears to be reflected in an allocation shift, in favor of the line judgment task, and against classification when each is time-shared with tracking.

Figures 5b and c: Classification and line judgement. As with tracking, the main effect of task pairing was statistically reliable for both of these tasks. (Classification: Wilks Lambda = .155, approximate $F = 79.53$, $p < .001$; Lines: Wilks Lambda = .259, approximate $F = 49.75$, $p < .001$). Both of these tasks manifest similar qualitative interference patterns. Both show maximum interference with themselves (or each other), an intermediate level of interference with the auditory task, and minimum interference with tracking. Again, this is a pattern of interference effects that is consistent with the structural theory, if it is assumed that the shared similar discrete response type of the auditory task provides a more dominating interference effect than does the shared visual input channel with tracking. The mutual sharing of both input channel and response type seems to lead to maximum interference between the classification and line judgement task.

In both tasks, planned multivariate contrasts were conducted between each adjacent pair of points in figures 5b and c. All such contrasts were statistically reliable at the level $p < .01$, so that it can be asserted that the apparent interference patterns of figures 5b and c are in existence. An interesting characteristic of figure 5b is that the classification points lie predominately to the lower right below the "equal allocation" positive diagonal. This suggests that the classification task, which was subjectively reported to be the least demanding, is also the task whose performance is most sacrificed by concurrence, a result supporting an earlier assertion make by Welford (1968), and more recently by Navon and Gopher (1979).

Figure 5d: Auditory task. Statistical analyses were not conducted on the auditory sharing data, because all points in figures 5d had, in fact been included in the three previous analyses. However, an important observation that has not yet been reflected by consideration of these figures concerns the apparent greater interference of classification, as opposed to line judgment with the auditory task; this despite the apparent lesser difficulty of the former task.

This difference conceivably reflects the structural overlap of the verbal alpha-numeric processing of the auditory and classification tasks, in contrast to the spatial processing required of line-judgment. Such interference patterns possibly reflect the greater competition within, versus between cerebral hemispheres for processing resources by the two tasks. This is a point that will be addressed in greater detail in the following section.

Hemispheric laterality effects

As noted above, the experimental design replicated each task pair twice, reversing the hand of response and display offset direction on each occasion. If the central processing demands of a given task are in fact lateralized, (spatial processing right, verbal processing left) then it is predicted that maximum time-sharing efficiency should result when the responding hand for that task receives motor commands directly from its processing hemisphere, and not vice versa. Under these circumstances, a certain amount of "hemispheric integrity" can be maintained when two lateralized tasks are time-shared.

Some experimental support for this lateralization hypothesis was provided by the current data. Two tasks--the auditory and number classification--are clearly verbal categorical in their processing demands, and these could readily be labelled as "left hemispheric". On the other hand, line judgement and tracking both have apparent spatial processing components, and thus may well be right-hemisphere lateralized. According to the argument presented above, a handedness asymmetry is predicted whenever one of the first pair (verbal) is time-shared with one of the second (spatial). That is, this assymetry should be manifest in the combinations TC, TA, LC and LA.

The data presented in figure 6a, showing a separate POC point for each hand, indicate a robust lateralized effect in the case of the tracking-classification (TC) pair. Thus whereas single task tracking performance is actually slightly poorer with the left hand than the right, when time-shared with classification a strong advantage of left hand tracking and right hand classification is shown over the opposite pairing. The statistical reliability of this effect may be assessed by considering its magnitude, relative to the $\pm$ 1 standard error confidence brackets surrounding each point.

The line judgment-auditory pairing also demonstrates this handedness asymmetry albeit to a lesser extent. Figure 6b indicates improved efficiency when the line judgment task is performed with the left hand (which presumably receives motor commands directly from the spatial-processing right cerebral hemisphere). While not as robust as in figure 6a, the effect here is still reliable, as indicated by the non-overlap of the confidence intervals around the two points.

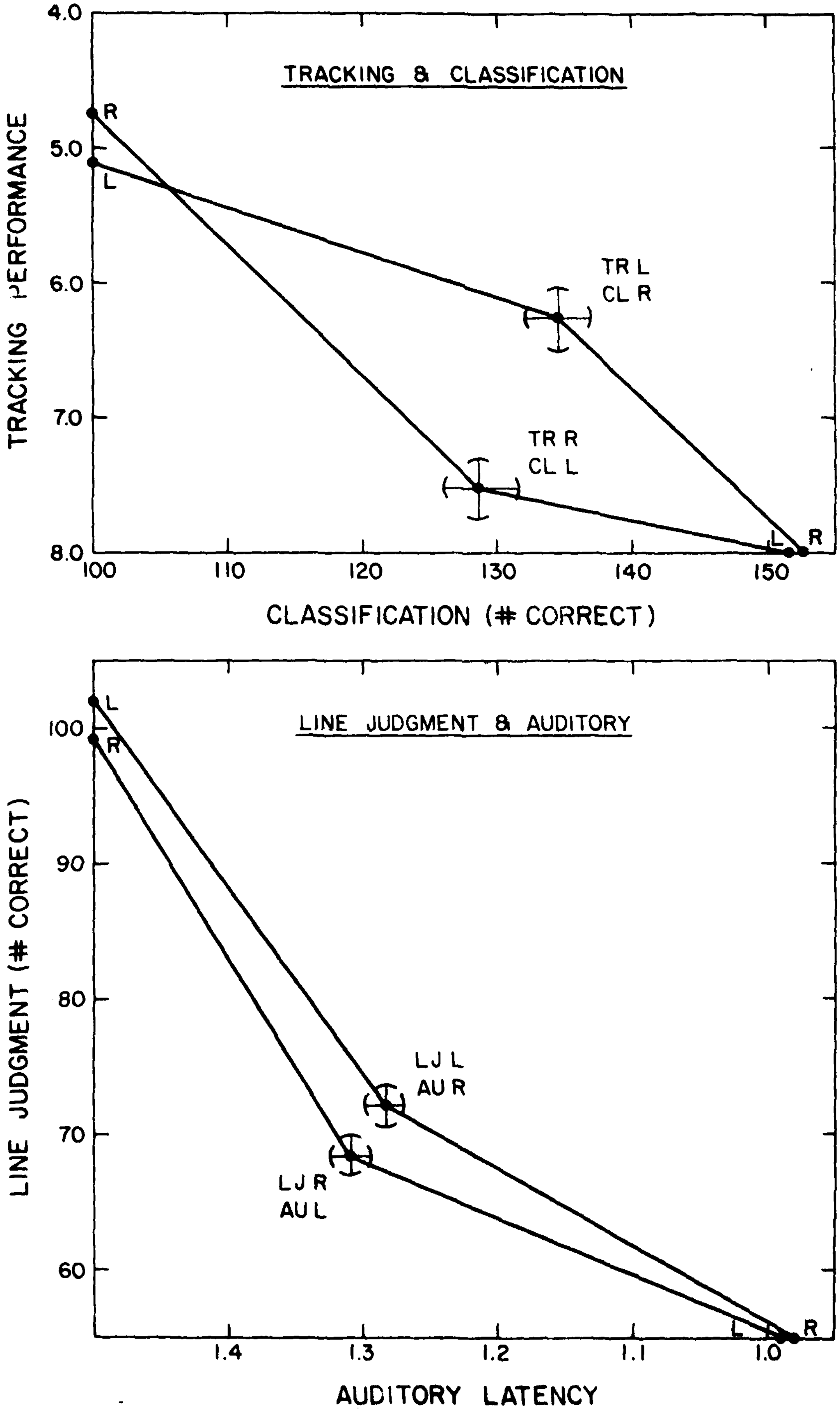

Figure 6: Hemispheric laterality effects. Performance as a function of hand pairing.

It should be noted that while the above comparisons argue that the classification and auditory tasks are left lateralized, while line judgment and tracking are right, the other relevant task pairings, TA and CL do not demonstrate a handedness time-sharing asymmetry. There appeared to be no reliable difference in efficiency in either direction as a function of the hand assignment.

Individual differences: Single task performance

Table 3 presents the correlation matrix of single task measures. It is evident from this matrix that some common abilities are tapped by all four tasks. In particular the classification task correlates highly with line judgment, and reliably with the auditory task. This pattern logically relates to the shared pacing characteristics, visual input and discrete response in the former case, and the shared verbal categorized processing and discrete response in the latter.

Individual Differences: Factor analysis

Two classical factor analyses were performed on the data (SPSS factor program PA2 with Oblique Rotation). The first, involving eight variables was performed on the single task measures and the average (across paired tasks) dual task measures for each task. The objective of this analyses was to determine if a separate factor, loading only on dual task combinations emerged. The second analysis focussed exclusively on the decrement scores. In this analysis the average decrement in each time-sharing condition represented the basic datum. There were 9 such time-sharing combinations (TT, CC, LL, TC, TL, TA, LC, LA and CA) and therefore 9 variables. In both analyses, a two factor solution was initially specified. This limitation was imposed in order to avoid capitalizing on chance, given the relatively small number of cases (40) and variables (8 and 9) (Humphreys, Ilgen, McGrath and Montanelli, 1969).

Single and dual task analysis. In this factor analysis, estimates of commonalities achieved through iteration were placed in the main diagonal, and an oblique rotation was performed on the factors extracted from the four single and four dual task measures. The initial correlation matrix is shown in table 4. After the initial factor extraction, two factors were observed to have eigenvalues greater than 1. The first factor, loading primarily on the single and dual task line judgment and classification tasks accounted for 51% of the variance (eigen-value = 4.07). The second factor, loaded primarily on the two tracking conditions (single and dual) and accounted for 23.9% of the variance (eigen-

Table 3

Single Task Correlations

	Tracking Class	Lines	Aud.
Tracking	.21	-.09	.37
Class		.63	.42
Lines			.29

Table 4

Correlation Matrix

Single and Average Dual Task Measures

(S = Single, D = Dual)

	S Track	D Track	S Class	D Class	S Lines	D Lines	S Aud	D Aud
S Track		.84*	.21	.26	-.09	.21	.37	.31*
D Track			.17	.21	-.09	.17	.25*	.20*
S Class				.87*	.63	.67	.42	.44
D Class					.67	.86*	.51	.64
S Lines						.75*	.19	.25
D Lines							.29	.55
S Aud								.67*
D Aud								

Table 5

Single-Dual Task Factor Pattern Matrix

	(a) Two Factor Solution		(b) Three Factor Solution		
	Factor 1	Factor 2	Factor 1	Factor 2	Factor 3
S Track	-.03	.95*	.02	.90*	.08
D Track	.02	.84*	-.03	.95*	-.09
S Class	.82*	-.02	.73*	-.07	-.14
D Class	.98*	-.06	.79*	-.07	-.29
S Lines	.79*	.31	.90*	.13	.14
D Lines	.87*	.01	.87*	-.10	-.01
S Aud	-.42*	.32	.03	.02	.80*
D Aud	-.04*	.25	-.10	-.03	.80*

* $p < .01$

value = 1.91). The initial factor matrix was subjected to an oblique rotation, and the final pattern matrix is shown in table 5a. An oblique, rather than orthogonal rotation was chosen because of the logical possibility that the factors emerging might well be correlated with each other, particularly as these pertain to time-sharing. The correlation between the two rotated factors was .219.

The same data were then reanalyzed with a three factor solution to assess whether the existence of a time sharing factor might emerge, acknowledging the greater likelihood of capitalizing on chance factors in this analysis. In the 3 factor solution however, the same initial factor emerged, while the second and third factor loaded heavily on the tracking and auditory tasks respectively (table 5b). Thus none of the three factors that collectively accounted for 87% of the variance, show a loading that is exclusive to dual task conditions. Each factor is restricted to a particular task (or in the case of factor 1, the pair of discrete, self-paced, visual tasks) and no "A" factor of time sharing was in evidence.

Decrement score analysis. Equivalent procedures to those described above were employed in the factor analysis of the nine total decrement scores. The correlation matrix of this analysis is shown in table 6, with the underlined cells representing correlations between task pairs posessing no common elements. In the initial two-factor solution, the first two factors had eigen values of 3.61 and 1.85, accounting for 40 and 20.6% of the variance respectively. The factor pattern matrix following oblique rotation is shown in table 7a. The first factor loads heavily on line judgment, paired with a visual task, particularly LL and LC, with a smaller loading on LT. The only other variable loading on this factor is the CC pair. Factor 2 unambiguously loads highly on all three time-shared auditory task conditions. In interpreting these loadings it should be noted that the decrement scores are themselves partially correlated with the single task measures. These correlations are in the range of .40 to .50 for the three discrete tasks, while they average to nearly zero for tracking. Thus it is possible that some portion of the loading of the dual task decrements may represent a reflection of individual differences in the single task performance itself.

When the decrement analysis was repeated with a three factor solution (table 7b), the same initial two factors emerged, along with a third factor that appears to load on the tracking and classification tasks, paired with themselves and with each other. This factor accounts for 14% of the total variance.

Table 6

Decrements Correlation Matrix[a]

	TT	TC	TL	TA	CC	CL	CA	LL	LA
TT		.23	.01	.23	.22	-.12	.29	-.17	.07
TC			.42*	-.04	.24	.15	-.01	.17	-.11
TL				.34	.20	.48*	.32	.62*	.48*
TA					.22	.20	.59*	.18	.75*
CC						.71*	.43*	.44*	.23
CL							.29	.85*	.36
CA								.10	.81*
LL									.29
LA									

[a]Underline indicates correlations between pairs with no tasks in common

* *p* < .01

Table 7

Decrement Factor Pattern Matrix

(a) Two Factor Solution

TT	-.11	.27
TC	.27	-.07
TL	.55*	.24
TA	.09	.74*
CC	.53*	.18
CL	.95*	.02
CA	.11	.84*
LL	.92*	-.07
LA	.19	.88*

(b) Three Factor Solution

	Factor 1	Factor 2	Factor 3
TT	-.27	.19	.56*
TC	.20	-.15	.40*
TL	.52*	.26	.03
TA	.04	.74*	-.21
CC	.46*	.11	.50*
CL	.90*	.07	.08
CA	.00	.81*	.22
LL	.96*	.00	.12
LA	.17	.97*	-.21

p < .01

The analysis of decrements clearly does not indicate the existence of any "general" time-sharing factor which loads on qualitatively different dual task combinations. Only the third factor provides a suggestion of such an ability, loading on the CC and TT pairs separately, even with the single task correlation between these two tasks being relatively low ($r = .21$). However this factor must be treated with caution. Because of the absence of any logical and theoretical interpretation--its emergence may well be attributed to random factors. Further evidence against the existence of a transituational time-sharing ability is provided by examining the correlation of decrement scores between all conditions that did not share a common task. These are the 12 underlined values in table 6. The mean value of these correlations is +.12, a value which drops to +.09 if the single high correlation between CC and LL is deleted from the average.

Speed Accuracy Set

A final analysis of interest concerned the subjects' "set" for speed vs. accuracy in the two visual discrete tasks (classification and line judgment). The performance measure employed for those tasks--number correct--was of course insensitive to whether a loss in performance was due to more errors committed at an equivalent response rate, or to slower responses with a consistent accuracy. In order to capture this dimension of performance, a speed accuracy set measure was computed from the formula $SA = K_1$ (% errors - K_2 x mean latency). This measure would yield low scores for slow accurate responding and high values for rapid, but error-prone responses. The values of K_2, the relative weighting of two components in the measure was based upon the ratio of day 2 - day 3 variability of the two measures; that is analogous to the consistency measures employed to weight performance on two tasks in computing decrement scores, as described above.

Greatest interest in these measures concerned the change in set induced by task loading. The SA values are presented in figure 7 for the single, and various dual task combinations of the classification (7a) and line judgment (7b) tasks. A remarkably consistent pattern of results is obtained here. Pairing each task with either of the tracking or auditory tasks renders the "set" for speed vs. accuracy unchanged; while pairing each with itself or the other induces a marked shift in bias toward the "slow but accurate" end of the speed-accuracy tradeoff, concomittant with the overall performance loss induced in the dual task environment. Thus, behavior changes resulting from dual task competitions may be manifest not only in overall performance scores (e.g., number

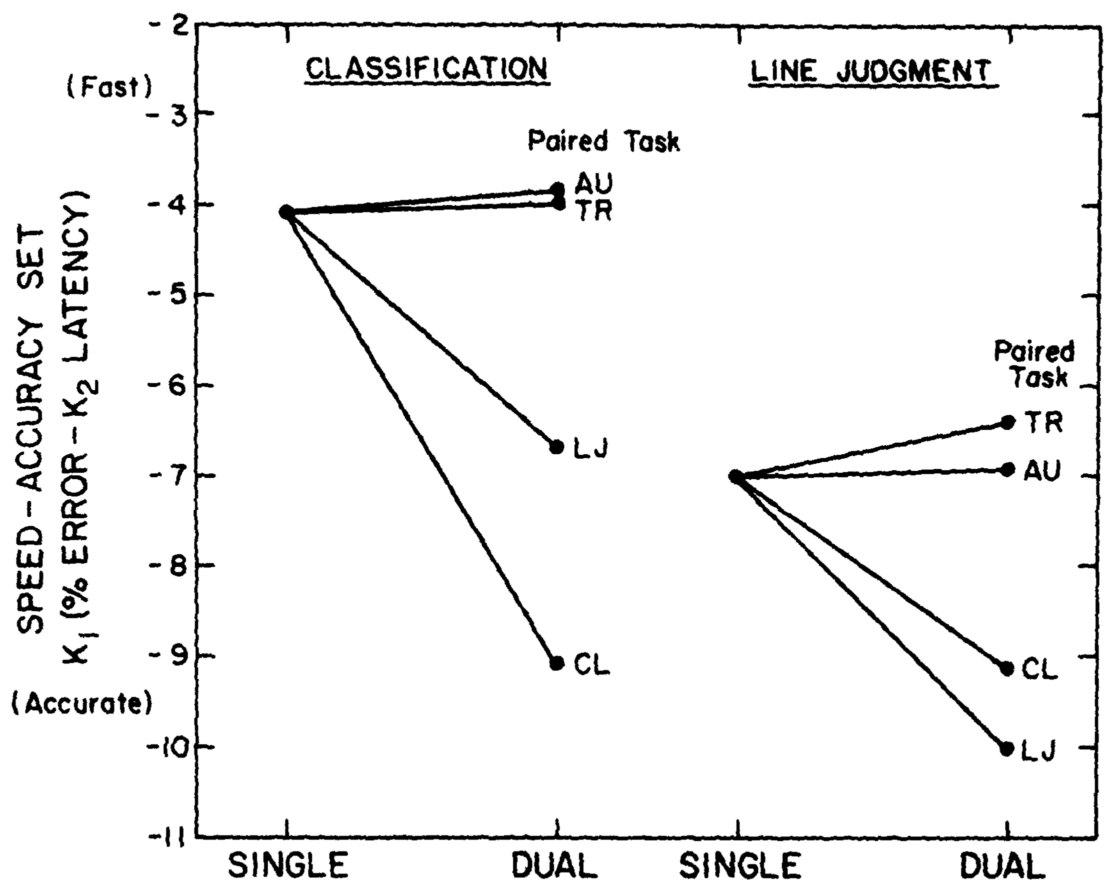

Figure 7: Change in speed-accuracy set induced by dual task loading.

correct), but in bias, or "set" measures as well, such as the speed accuracy index described above.

DISCUSSION

The present data provided little concrete evidence for a transituational "A" factor of time-sharing efficiency, thus supporting the conclusions in this regard offered by McQueen (1917), Sverko (1977) and Jennings and Chiles (1977). Within the power of the present experimental design (which did not allow for more than 3 factors to be reliably extracted), no factor from the first analysis emerged that loaded exclusively on time-sharing conditions. The factorial structure of the three factor solutions was a direct reflection of the dimensions of individual differences in single task performance. When the specific source of decrements were examined in the second analysis, these again tended to be closely alligned with the dimensions of single task performance, as indeed these decrements appear to be highly correlated with the single task measures.

What did appear to emerge from the second analysis is a dimension of time-sharing concerned with the visual spatial task paired with another visual task (such that the line judgment task is a common element), and a second dimension of time-sharing involving the auditory-memory task. The first factor may be related to visual monitoring strategies and therefore be identified with Jennings and Chiles' (1977) single observed time-sharing factor. This factor is clearly specific to the perceptual or visual aspects of the task, because of its low loading on the auditory-line combination even though these tasks share common response elements. Further clarification of this factor emerges if one rank orders the apparent acuity demands of the tasks from line judgment (greatest) to classification to tracking to auditory (least). Task pairs such as LL or LC that possess the greatest joint acuity requirements, and therefore entail the greatest need for optimal scanning strategies to bring the stimuli into foveal vision at appropriate times, will load most highly on this factor. The lower acuity requirements assumed for tracking is consistent with the observation that this task can be performed in peripheral vision without extensive decrement (Levison, Elkind and Ward, 1971).

Two alternative interpretations may be proposed for the second factor, loading on the three auditory combinations. As a pure time-sharing ability, it might be related to the efficiency of switching between auditory and visual modalities (LaBerge, Van Gelder and Yellott, 1975; Hawkins, Church and DeLemos, 1978). An alternative and plausible interpretation in light of the high correlations between the single task auditory scores and the auditory decrements, suggests that this ability may be related to differences in automation or capacity within short term memory. Those individuals able to store the auditory letters with fewer resource demands would correspondingly, be able to time-share a second task more efficiently. This interpretation substantiates conclusions drawn by Lansman (1977) concerning the correlations between memory performance in single and dual task conditions.

Concerning the third factor that emerged in the decrement analysis, loading on the TT, CC and CL pairs, little can be asserted with confidence, because of the relatively small proportion of variance accounted for (14%) and the absence of any common elements, or "natural" underlying dimension subsuming these tasks. It is tempting to suggest that the factor may relate to hemispheric separation, because of the large laterality effects observed with the classification-tracking task pair (figure 6a). Such a factor would also relate to individual differences in this dimension suggested by Elithorn and Barnett (1967). However such post hoc speculation concerning a relatively small effect can be offered only with extreme caution.

The presence of high correlations between single and dual task performance, and the absence of specific time-sharing factors from the first factor analysis seemingly contradict previous research findings reported by North and Gopher (1976) and Trankell (1959) in which, larger portions of variance in dual task performance were not accounted for by single task variance. These discrepancies may be resolved if it is assumed that a large component of the obtained individual differences in time-sharing are attributable to automation of single task skills. Accordingly it may be argued that individuals through practice stabilize at maximum asymptotic levels of single task performance. However, further differences in practice, or overlearning allow these levels to be obtained with differing demands for processing resources (variance in automation). These differences are latent to the extent that they will not be revealed until the portion of those resources not utilized (spare capacity) is as demanded by a concurrent task in a time-sharing situation. This proportion will then be reflected in the dual task performance of one, or both tasks, depending on how resources are allocated.

This relation is depicted in the form of the change in the hypothetical performance resource function (Norman and Bobrow, 1975), that occurs at two levels of practice, (see figure 8), or between two individuals with differing levels of automation. At maximum performance the two (A & B) are nearly equivalent. Only with a portion of resources diverted to a concurrent task do the differences emerge. Lansman (1977) offered this explanation to account for her observation of individual differences in performance of a time-shared memory task. As stated above, Lansman's findings suggest that the same mechanism may underlie the auditory memory factor observed here. To account for the high correlations between single task performance and dual task decrements, with the auditory task one need only assume that the level of asymptotic performance in the performance-resource function of figure 8, is reflected to some extent by the slope of this function.

Humphreys et al. (1969) have argued for the importance of replicability in factor analytic studies. Therefore the important characteristic of the results provided in the current investigation are those that replicate findings of previous researchers. These may be briefly recapitulated as (a) the absence of a general transituational time-sharing factor, (McQueen, 1917; Sverko, 1977; Jennings and Chiles, 1977); (b) the most important task specific time-sharing factor emerging from the decrement analysis being the visual task-sharing factor (Jennings and Chiles, 1977) and (c) a second factor loading on dual task short term memory (Lansman, 1977) that appears interpretable in terms of automation, rather than time-sharing. With these exceptions, no other dimensions of individual differences were in evidence tl 'oaded heavily on a particular dimension of processing resources (response selection vs. execution, spatial vs. verbal categorical processing, or self vs. forced pacing). This negative finding does not imply that these dimensions were not reflected by the patterns of task interference however; only that they did not constitute dimensions along which individuals differed greatly. The evidence for the dimensions of performance provided by the decrement scores will now be addressed.

The dual task data were quite compatible with a structural interpretation that defines dimensions of processing resources by modalities of input, stages of processing and modalities of central processing. The comparisons that lead to these conclusions can be briefly reviewed.

(a) Modalities of input. The auditory task, sharing a different input modality from the other three appears consistently time-shared more efficiently with the other tasks, than do the other tasks with themselves. An exception to

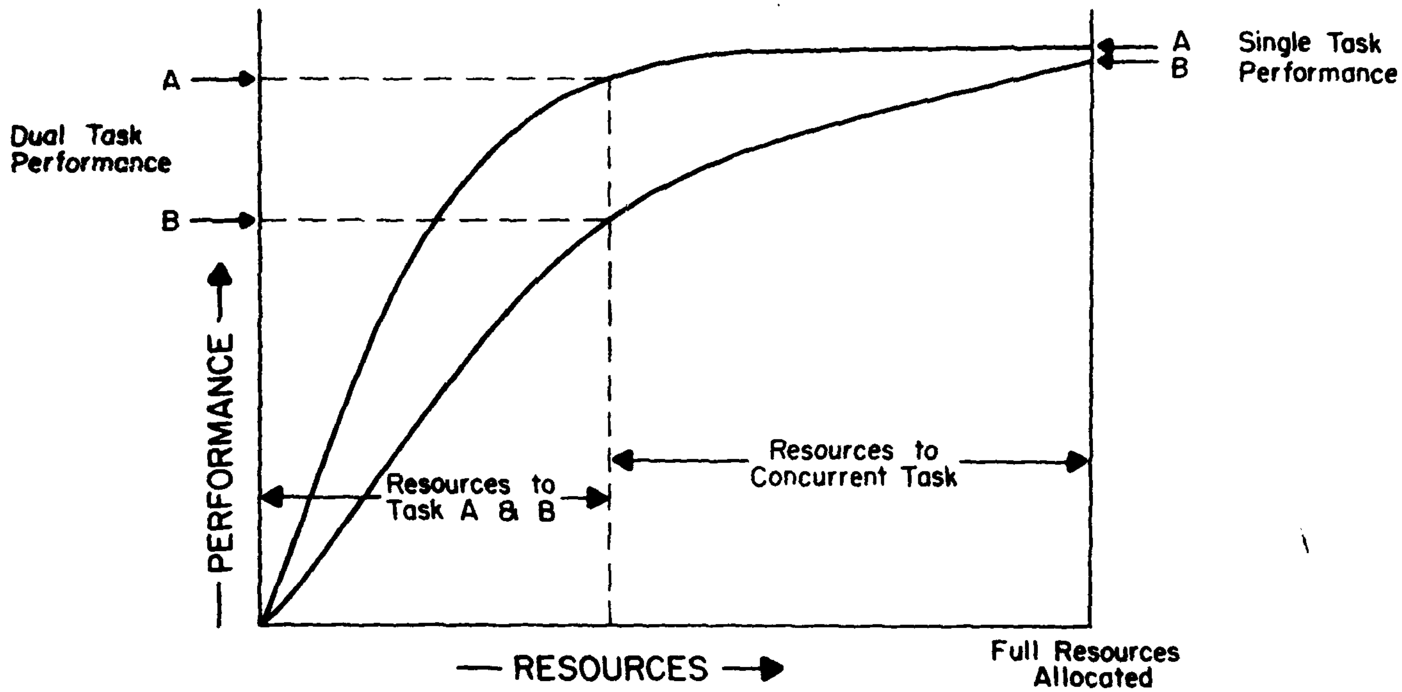

Figure 8: Hypothetical performance resource functions of two individuals differing on level of asymptotic performance and automation. Right axis: Single task performance, Left axis: Dual task performance.

this generalization concerns tracking shared with the discrete visual tasks (figure 5b and c). This exception can be explained by considering the processing dimension defined by stages of processing.

(b) Stages of processing. It is apparent from figure 5a, that the precision responses required in dual axis tracking interfere with each other, to a much greater extent than does the tracking response with the discrete key press responses required of the 3 discrete tasks. The reason for this differing interference pattern between discrete and continuous response, observed also by North (1977), may relate to differences in processing demands upon the stage of response selection, by the discrete tasks, and response execution by the continuous tasks This distinction has often been drawn by stage theorists of reaction time (e.g. Smith, 1968; Sternberg, 1969), and can be elaborated further by contrasting the selection of a motor program (response selection), with its execution, the latter relying upon continuous processing of proprioceptive feedback (Martenuik and McKenzie, 1979). In the present treatment, these two mental operations are posited to depend upon separate processing resource reservoirs, thereby minimizing interference.

(c) Modalities of central processing: spatial vs. verbal categorical. This dimension was perhaps the least salient, but its role was observed in both the main interference effects as well as the handedness analysis. Wickens (1979) has argued that verbal, categorical processing may rely upon qualitatively different processing resources from spatial processing, and extensive evidence suggests that this difference in resource pools may well be related to cerebral hemispheric specificity (Krashen, 1978; Kinsbourne and Hicks, 1978). In the present experiment two tasks, tracking and line judgment, were intended to load spatial processing, while the auditory and classification tasks were verbal-categorical in nature. Strongest evidence for this processing specific interference is provided in figure 5d, in which the auditory task is shown paired with tracking line, judgment, and with classification. Here interference with the classification task is reliably greater than with line judgment, despite the fact that these two bear the same relation to the auditory task in terms of input modality (both different) and response modality (both same). The critical interfering element appears to be the verbal categorical processing required by both the auditory and classification tasks, but not be line judgment.

As noted in the results section, further evidence is available to suggest that this spatial-verbal distinction is hemispherically defined. This is represented by the major benefits to dual task performance that accrue when tasks

of a given processing modality (and presumably processing hemisphere), are responded to with the hand directly controlled by that hemisphere. These results were demonstrated most visibly with the tracking-classification pair, and to a lesser extent with the auditory-line judgment pair. Such an arrangement avoids any "neural crosstalk" resulting from a single cerebral hemisphere processing information on one task, while executing the responses for the other.

(d) pacing. A fourth dimension along which the task pairs may be contrasted- related to whether the tasks are force-paced (tracking and auditory), or self paced (classification and line judgment). Figures 5b and c suggest that the sharing of two self paced tasks (CC, CL and LL pairs) generates greater interference than the sharing of a self with a forced task (CT, CA, LT, LA). However, it is impossible to determine from these data if this "pacing sharing" is the critical dimension underlying the interference pattern, since the pacing contrast is also completely confounded with the joint contrast of input modality (C, L vs. A) and response stage (C, L vs. T).

Competition vs. Coordination

The point has been articulated above, that the more common structures shared by two tasks, the greater will be the extent of interference. While the data in figures 5 and 6 are generally consistent with this viewpoint, two apparent exceptions emerge when contrasting the CC-CL and LL-CL pairs. In both cases an overlapping structure interpretation would predict greatest interference when the task was shared with itself (e.g., CC and LL). This indeed was observed with tracking, yet for the discrete tasks, there appeared to be little difference in decrement between the CC and CL pairs, or the CL and LL pairs. A possible reason for this equality is that, while there may be a cost to performance associated with two tasks requiring common structures (competition), there can also be a benefit, associated with the need to activate only a single central processing mechanism (coordination). In the present case it may be easier to perform exclusively spatial judgments (LL pair) than to activate alternately spatial and verbal processors (CL pair). This advantage will outweigh, or at least balance the cost of overloading the spatial processing system as the two line judgment tasks are performed concurrently, and thereby preserve the equal decrements between the LL and CL combinations observed in figure 5c.

CONCLUSION

In conclusion the present results seem to indicate that dimensions of task-related differences in dual task performance efficiency are not necessarily alligned with the dimensions of individual differences in time-sharing efficiency. The former were clearly identifiable along the dimensions of processing resource reservoirs suggested by Wickens (1979), and described by stages, modalities and hemispheres of processing. On the other hand, individual differences in dual task efficiency that could not be accounted for by single task performance differences were not pronounced, and those that did emerge were not clearly alligned with the dominant dimensions of task interference. The most pronounced individual difference, the scanning/acuity factor 1 appears to be clearly a time-sharing ability in the second sense of the concept described in the introduction, but is related more to strategy and to the allocation of resources than to the availability or functional separation of the resources themselves. Besides this factor, it must be stated that the major abilities dimensions of dual task performance relate to dimensions of single task performance, both to the absolute level of that performance, and its level of automation. The quest for the "A" factor appears to be of no avail.

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